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Space Science with the SpacePy Toolkit

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Abstract

The open-source SpacePy toolkit (*Morley et al.*, 2010b) was first publicly released in August 2011. It has contributed to several published and ongoing studies in the space sciences. We review some results of these studies with a focus on how they were enabled by SpacePy and how it can facilitate other research in the field.

We also discuss SpacePy as an enabling technology for data processing and analysis for the Energetic particle, Composition, and Thermal plasma (ECT) suite on the Radiation Belt Storm Probes (RBSP) mission.

Introduction

Research in space sciences has historically relied heavily on proprietary, domain-specific software and specialty codes which are neither shared nor reused. There is often a strong disconnect between data exploration activities and final publication-quality plots.

The SpacePy project revolutionizes space science data analysis by leveraging best-in-class tools from the general computing domain and facilitating code sharing and re-use.

Our goal is simple: to do better science, faster, and cheaper.

Python and SpacePy

Python is a general-purpose, multi-paradigm (OO encouraged) programming language that supports both interactive and scripted mode. *We leave language design to the computer scientists*.

Python is the 8^{th} most popular programming language. Matlab is 19^{th} (and dropping). IDL falls into the 50-100 category. (TIOBE index)

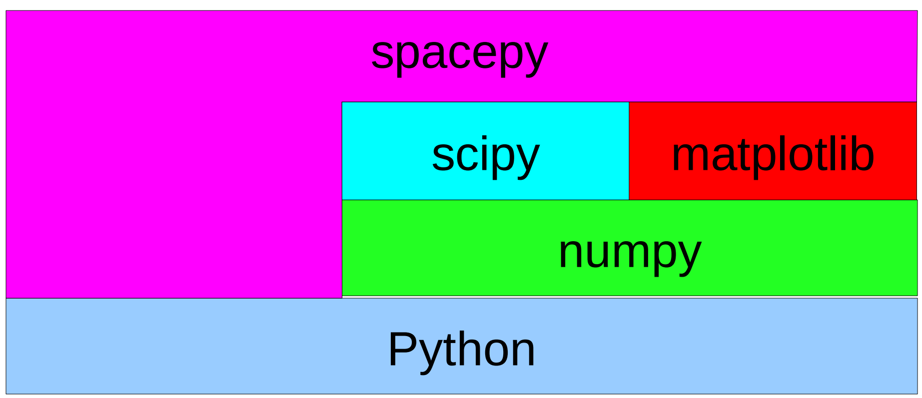
numpy provides high-efficiency array types and operations.

scipy adds many useful scientific, mathematical, and statistical operations.

matplotlib has excellent plotting capabilities, from browse to publication.

SpacePy builds on this base with space science specific functionality.

All are freely available and open source (BSD and GPL compatible)



Development approach

- SpacePy is not directly funded: modules are written as needed for doing our work (and we're glad to help you do yours!)
- Leverage existing code and projects, preferably with wide userbase (matplotlib has broader appeal than space physics, why roll our own? Even moreso for Python itself)
- Combination of Python, C, and Fortran
- Distributed version control with git
- Moving towards more open *development* process, see repository at http://sourceforge.net/projects/spacepy/
- Standards for inclusion:
  - *generally useful* across multiple space science projects (not one-off)
  - *tested* (341 unit tests across the package)
  - *documented* via Python “docstrings” that provide both on-line help and rendered HTML and PDF documents (via Sphinx)

The SpacePy data model

- Lightweight unifying “container” types
- SpaceData objects contain:
  - attributes, indexed by name or number, not ordered
  - data, indexed by name or number, not ordered, any type
- dmarray objects contain:
  - attributes, indexed by name or number, not ordered
  - data array, any dimensionality, any type
- attributes themselves can be any type, describe data attached to
- Matches organization of
  - NASA Common Data Format (CDF), from SpacePy's pycdf module
  - Hierarchical Data Format (HDF5)
  - lightweight ASCII-based format with machine-readable JSON header, common between SpacePy, autoplot, LANLGeoMag
- Easy conversion among formats!
- Metadata in attributes usually interpreted according to ISTP standards

The SpacePy data model (2)

Example SpaceData object from reading an OMNI CDF from CDAWeb

SpaceData

attrs
Discipline: Space Physics>Interplanetary Studies
TITLE: Near-Earth Heliosphere Data (OMNI)
...

Epoch:

dmarray

attrs
FIELDNAM: Epoch Time
SCALEMAX: 2020-12-31 23:59:59
...

2012-01-01 00:00:00, 2012-01-01 01:00:00, 2012-01-01 02:00:00 ...

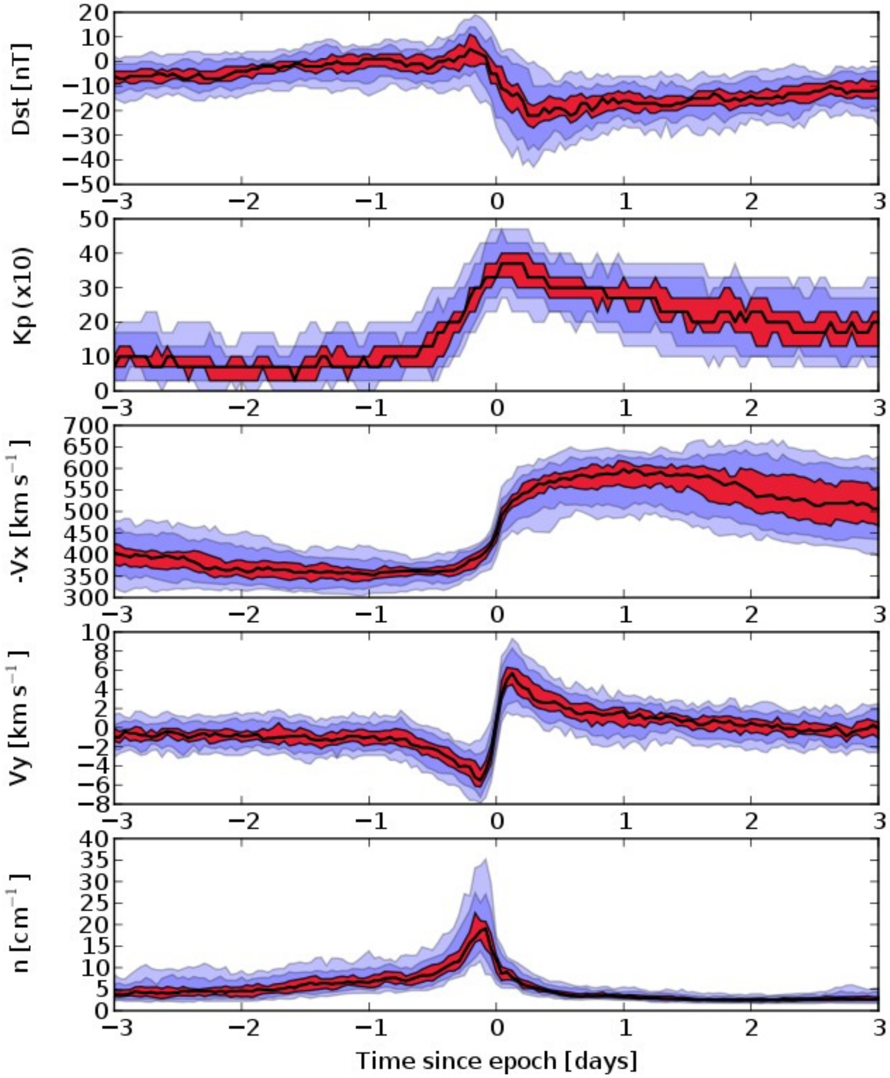
N:

dmarray

attrs
FIELDNAM: Ion density
DEPEND_0: Epoch
...

6.1, 7.9, 6.9, 6.7 ...

High speed streams and radiation belt dropouts: superposed epoch analysis

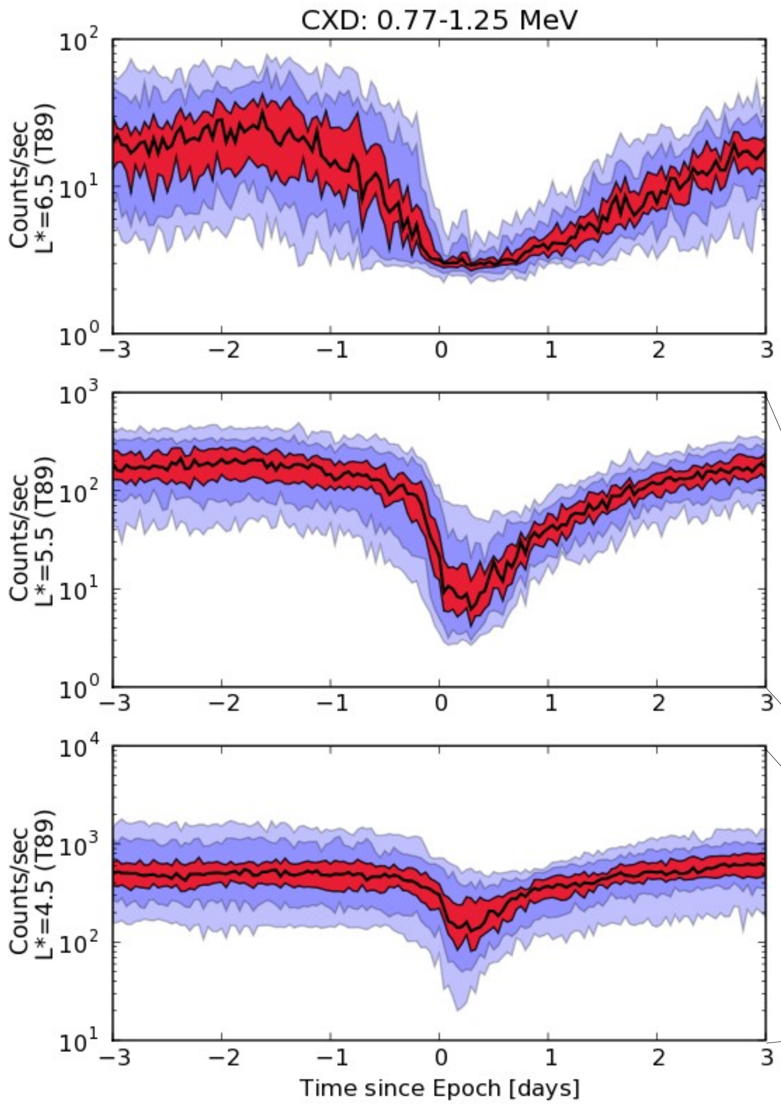


The radiation belt dropout study of *Morley et al.* (2010a) used the SeaPy module to perform superposed epoch analyses.

Both 1-D and 2-D superposed epoch analyses were performed to calculate the superposed medians (black lines) and IQRs (dark blue band) along with confidence intervals (red and light blue bands).

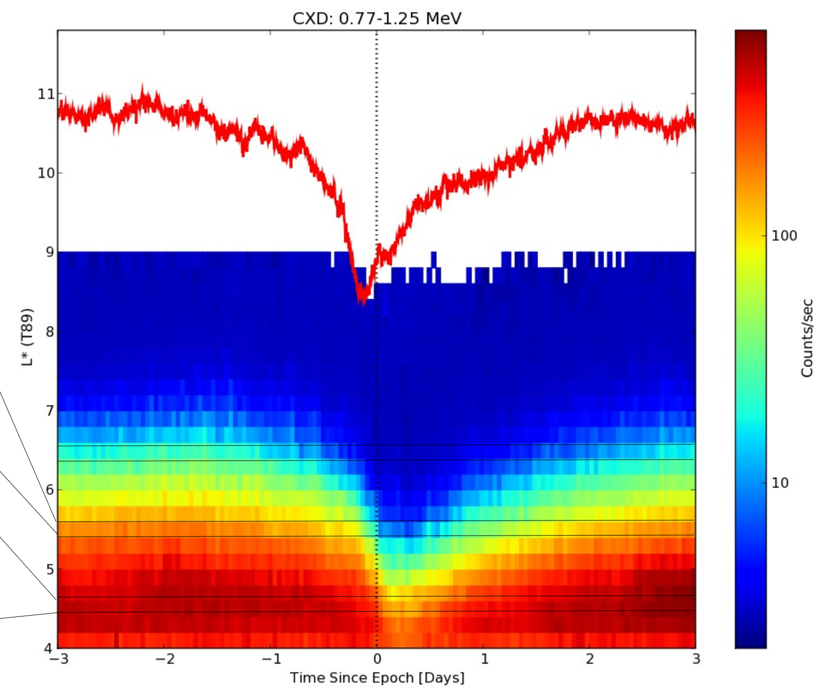
The plot shows the consistency of the stream interfaces (lower 3 panels) and the consistent, weak response in Kp and Dst. About 70% of these stream interfaces do not lead to Dst storms.

High speed streams and radiation belt dropouts: superposed epoch analysis (2)



2-D superposed epoch analyses of the GPS count data were performed for the set of stream interface epochs and 1-D slices were extracted.

For particle energies of ~1MeV a dropout is found at all measured L, driven by a pressure pulse, with no (or weak) attendant storms.



Cusp energetic particles and storms/substorms: association analysis

Connections have been proposed between energetic particles in the cusp (CEPs) and magnetospheric processes.

Niehof, Morley, and Friedel (2012) used the PoPPy (**Po**int **P**rocesses in **Py**thon) module of SpacePy and six years (1996-2002) of Polar and GOES data to examine whether storms and substorms are associated with CEPs.

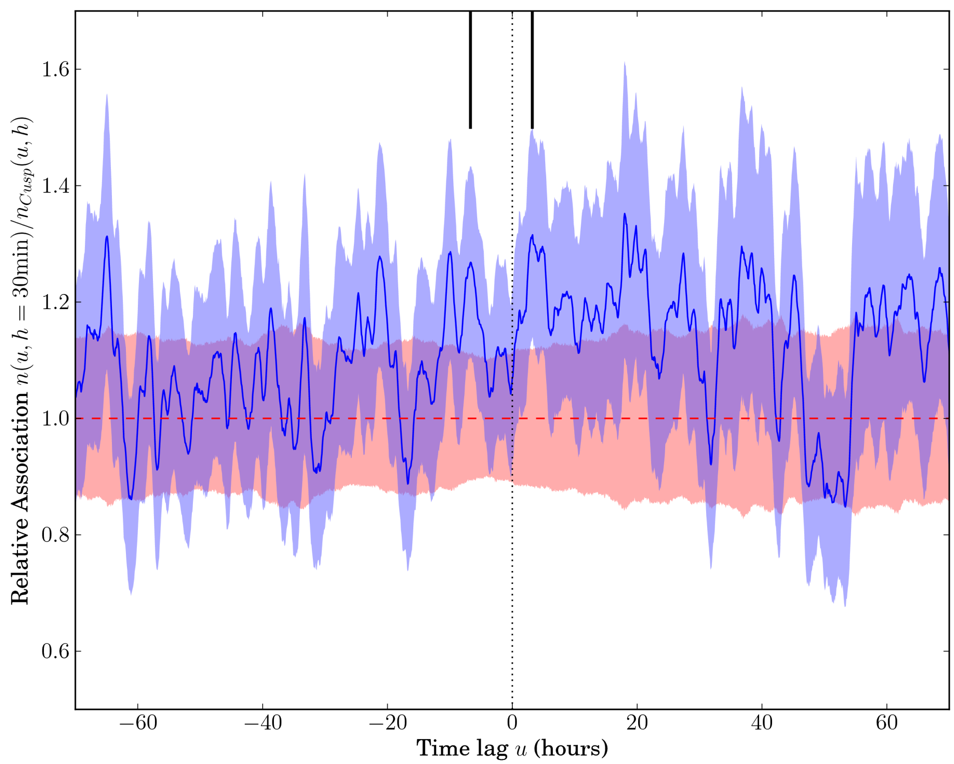
PoPPy combines association analysis with the bootstrap (*Niehof and Morley*, 2012; references therein) to determine the significance of the association between two series of events and the lag inherent in the association.

Cusp energetic particles and storms/substorms: association analysis (2)

The red band shows the 95% confidence interval for associations between cusp observations by Polar and field dipolarizations at GOES, associated with substorms. All associations are normalized to this cusp number to determine the association between dipolarizations and energetic particles specifically, i.e., to eliminate association based solely on when Polar observed the cusp.

The blue band shows the 95% c.i. for CEP observations, normalized to the cusp. There is an association between CEPs and dipolarizations at the 95% confidence level with CEPs lagging dipolarizations by about 3 hours (roughly half the drift period at CEP energies).

There is also an association, below 95% confidence, with CEPs leading dipolarizations, explainable by chance coincidence.



Efficient L* calculations via neural networks: LANLstar

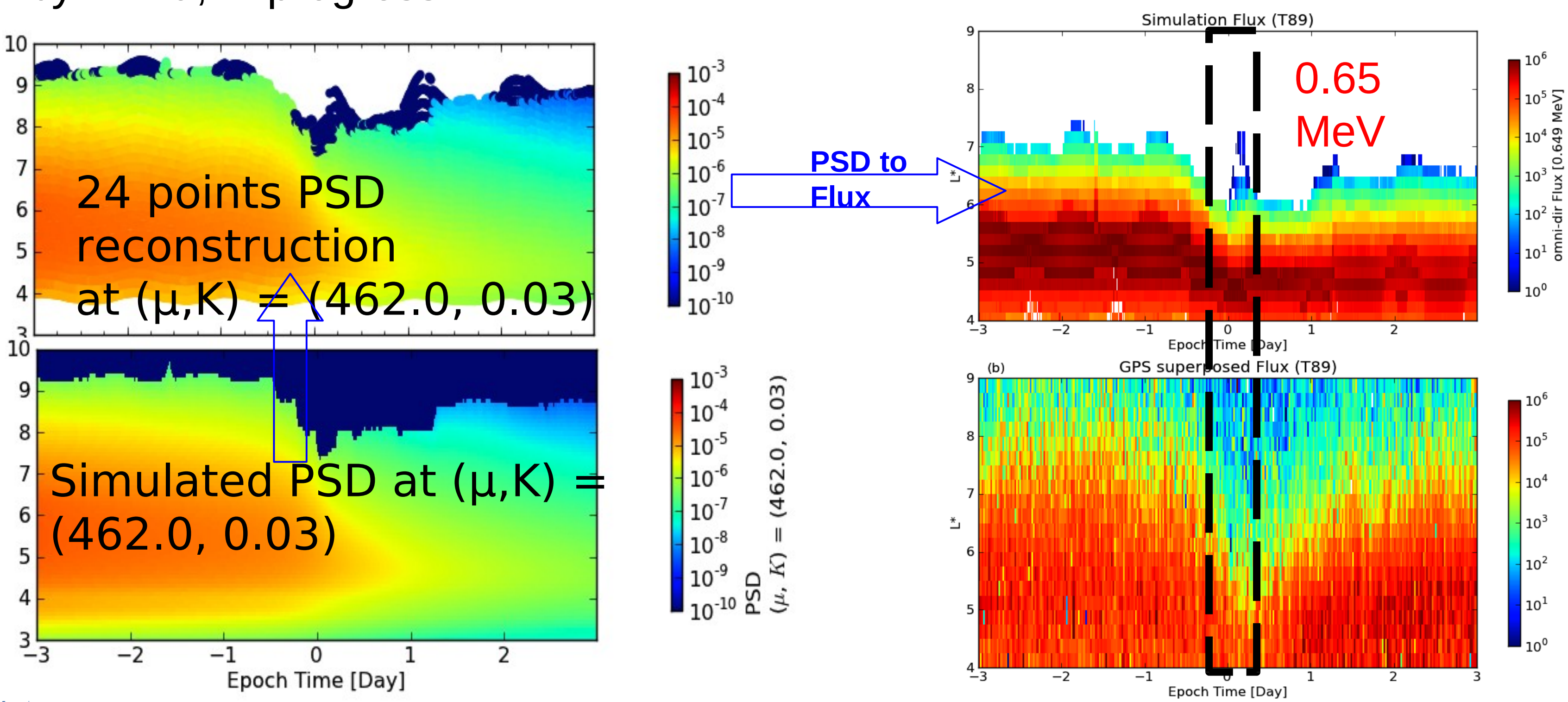
The LANL* project (*Koller and Zaharia*, 2011; http://www.lanlstar.lanl.gov/) provides fast calculations of the third adiabatic invariant, L*, using the ffnet feed-forward neural network ffnet (http://ffnet.sourceforge.net/)

SpacePy's LANLstar module provides an easy Python interface to the neural network. (The omni module provides easy access to solar wind and geomagnetic indices needed for network input.)

SpacePy provides LANL* instant run services to NASA's Community Coordinated Modeling Center, at http://ccmc.gsfc.nasa.gov/models/modelinfo.php?model=LANL.

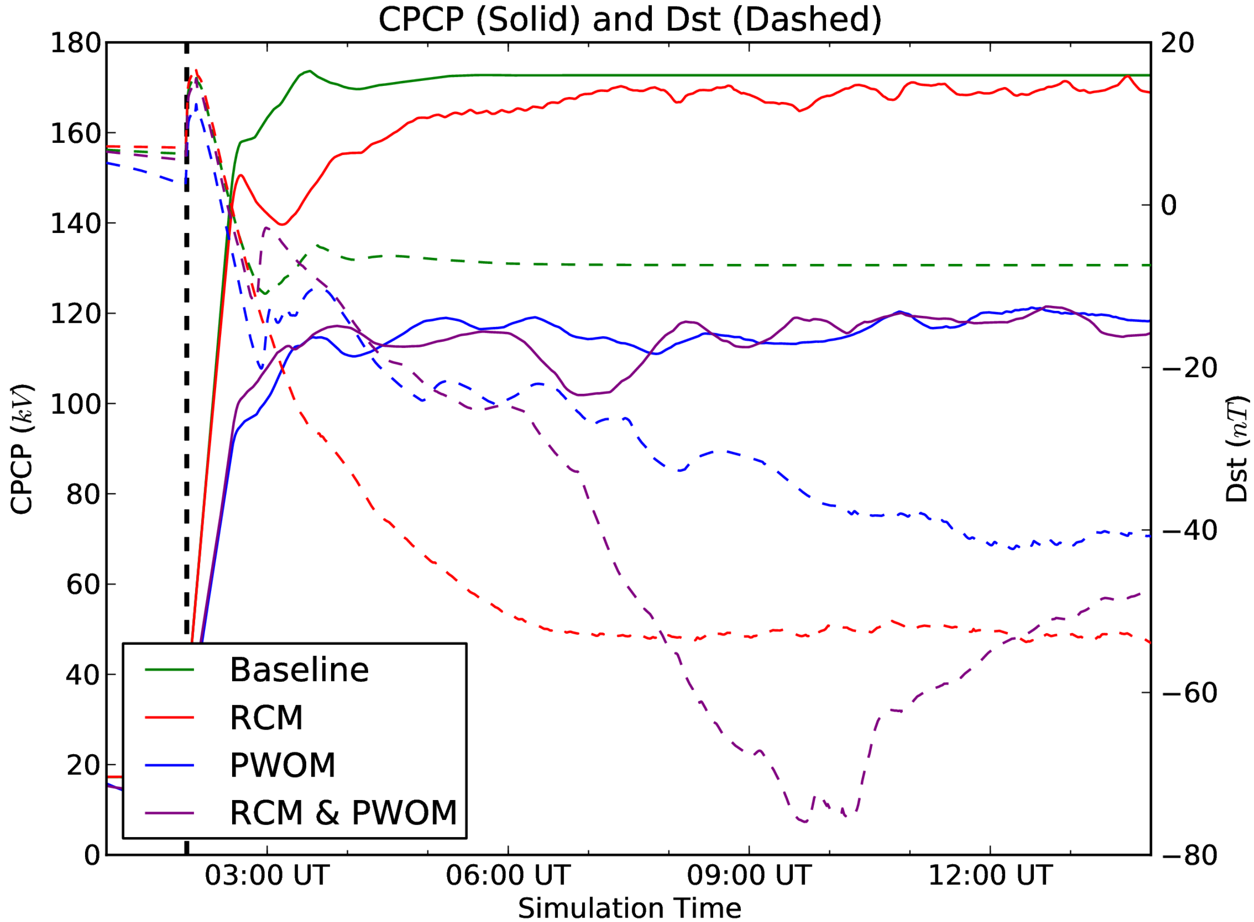
Radiation belt losses from magnetopause shadowing: LANLstar and SeaPy

- Calculate L* from ***SpacePy/LANL**** at equatorial midnight, 4-10 Re, 0.25 Re apart.
- Extract simulated PSD(μ,K, L*) at the drift shell L* for these points (based on radial diffusion and loss to magnetopause); convert to omni-directional flux (E).
- Bin flux profiles in drift shell L* space (if overlapped at the same L*, take the average).
- Compare with superposed GPS flux observations for 67 events from 2005-2008, organized by L*, using SpacePy's SeaPy (Superposed Epoch Analysis) module. Epoch time is from solar wind High Speed Stream interfaces.
- Work by Y. Yu, in progress



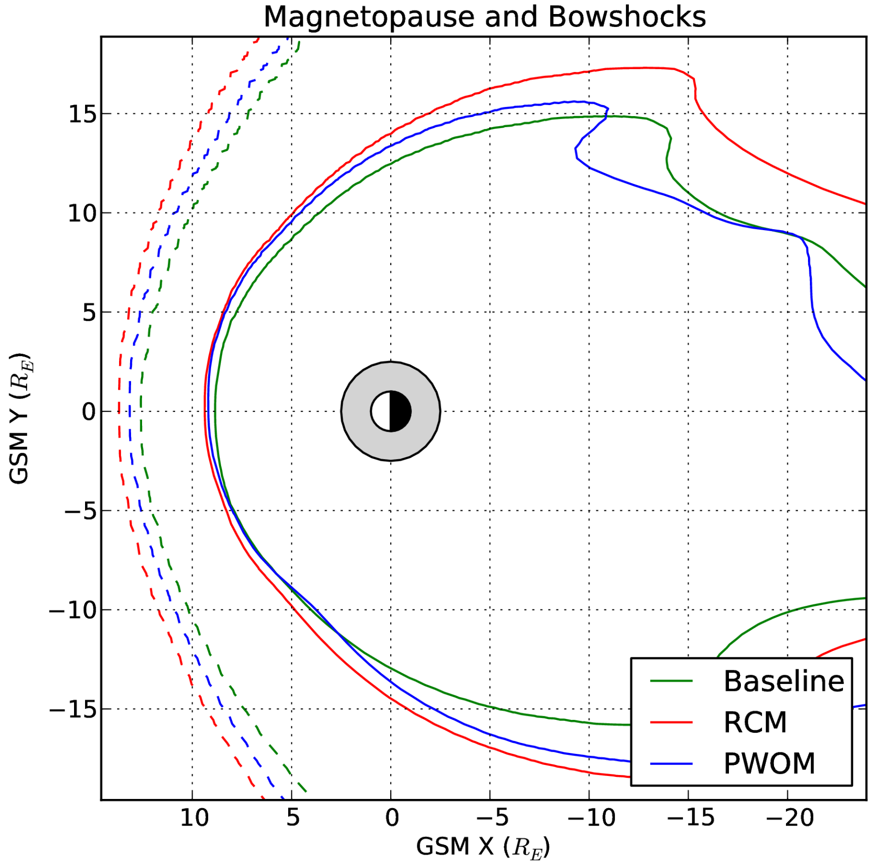
Ionospheric outflow and cross polar cap potential: visualization and analysis of global MHD simulations

Welling and Zaharia (2012) used SpacePy to analyze three different MHD simulations in terms of CPCP and Dst. The software extracted magnetopause and bowshock locations to analyze physical processes behind outflow-related CPCP reductions, a feature found universally amongst MHD codes that include polar-wind like outflow.



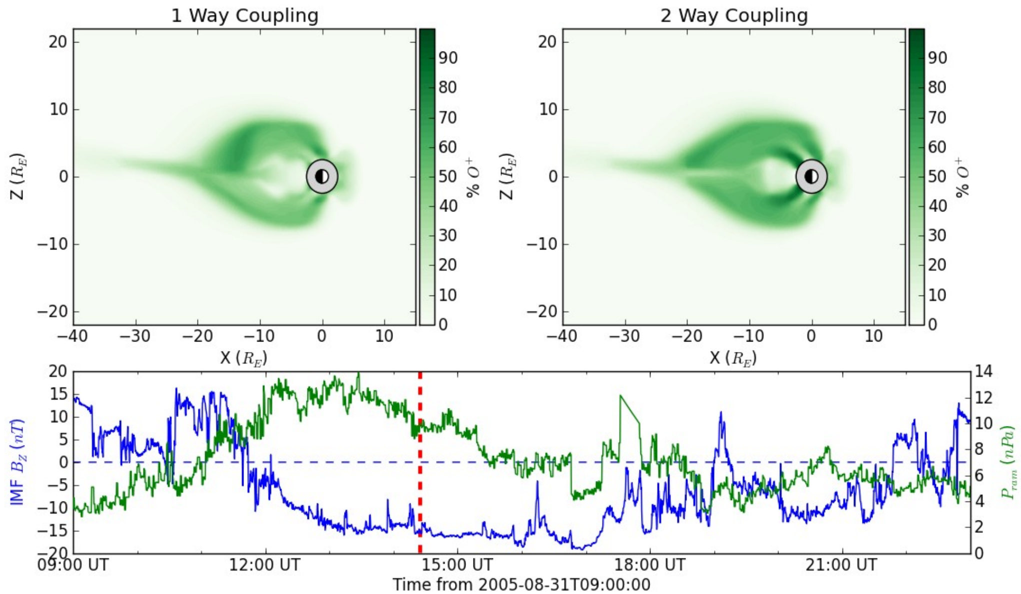
Ionospheric outflow and cross polar cap potential: visualization and analysis of global MHD simulations (2)

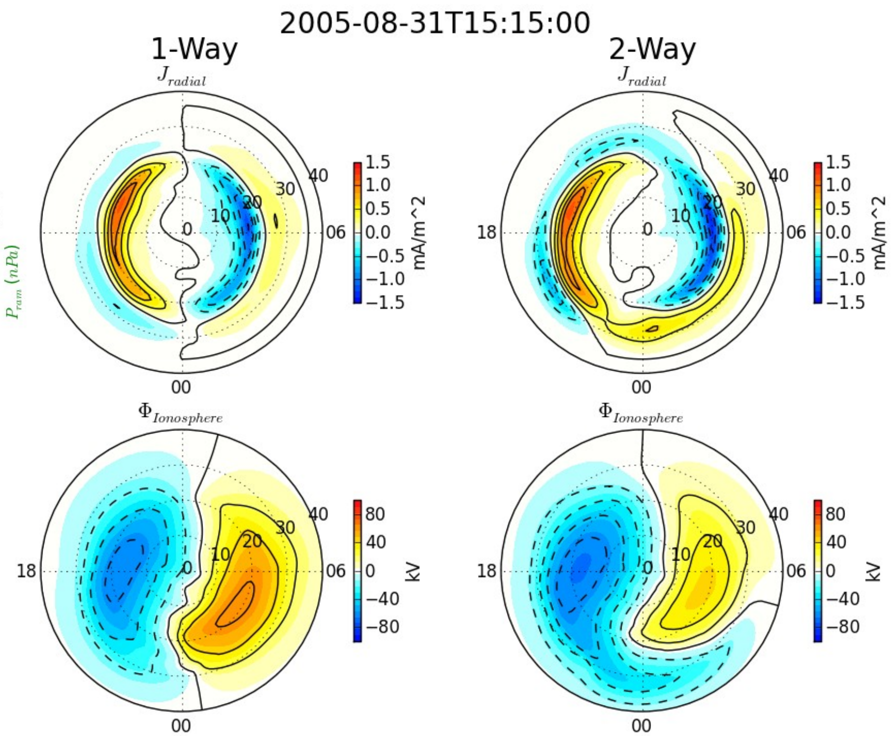
Brambles et al. (2010) predicted that outflow drives magnetospheric blunting, which in turn reduces the reconnection potential applied to the magnetosphere. *Welling and Zaharia* performed three idealized simulations to test this hypothesis: a simulation without outflow, a simulation with outflow, and a simulation coupled to a ring current model. The final simulation has the ability to blunt the magnetosphere without explicit outflow, providing a control to the experiment. It was found that the hypothesis presented by *Brambles et al.* does not solve the outflow-related CPCP reduction puzzle.



Ionospheric outflow and the ring current: visualization and analysis of global MHD simulations

Welling, Jordanova, and Zaharia (2011) explored the interplay between ionospheric outflow and the ring current using three separate coupled models. SpacePy performed the analysis that illustrated how R2 FACs may be a key driver of mid-latitude storm time outflows, which in turn drive ring current dynamics.



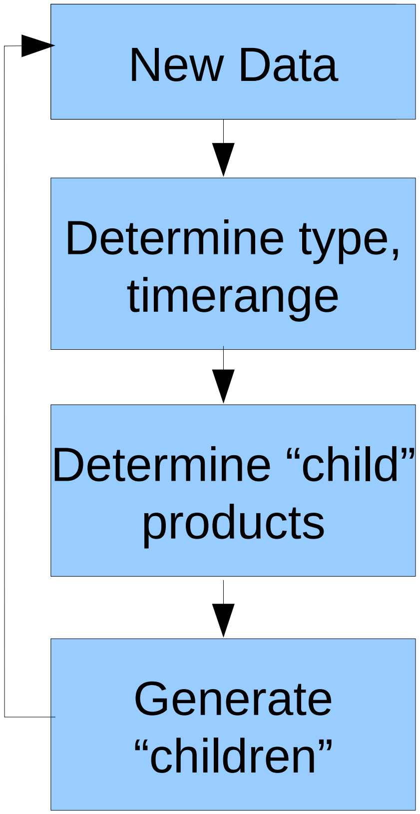


Supporting operations and data processing: the RBSP ECT SOC

ECT data processing was described in poster by *Friedel et al.* (2012) on Wednesday. SpacePy and Python are used for:

- access to data formats:
  - CDF read and write via pycdf
  - magnetic ephemeris files (from LANLGeoMag) via the datamodel
- conversion of data from MET to UTC
- HOPE level 1 (counts) to level 2 (calibrated flux) processing
- addition of common ephemeris information to all level 2 files
- tracking dependencies for all data and automatically processing/reprocessing as new data arrive
- instrument commanding and communication with MOC
  - calculation of execution mission time from UTC or orbit conditions (e.g., L)
  - support for recurring commands
  - verification of command upload and execution

ECT SOC data versioning and reprocessing

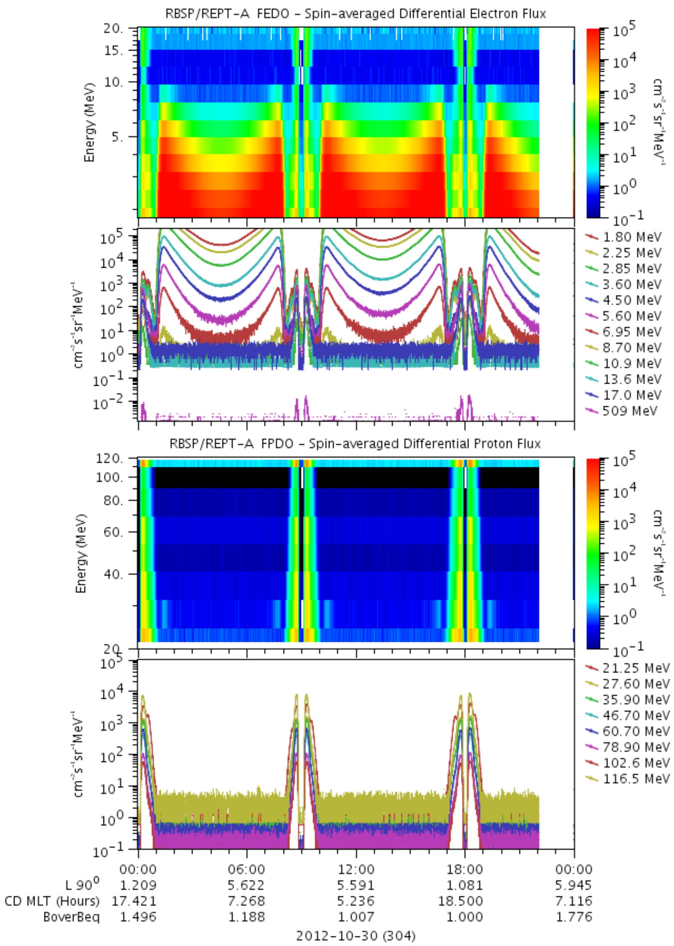


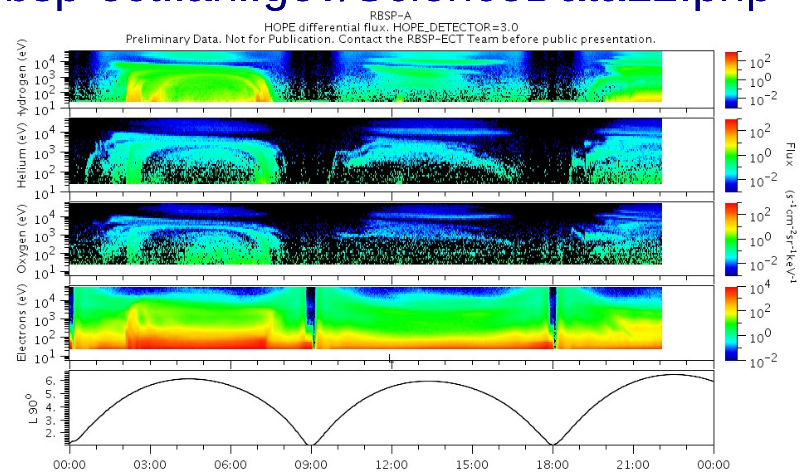
- **Versions of all data and code tracked**
  - Provenance known
  - Files can be regenerated to any version given L0 files and codes
- **Automatically regenerate if data, code updated**
  - e.g. regenerate all data for updated calibration table
- **Generic processing tool**
  - *Control* framework, actual codes for e.g. L0-L1 maintained separately

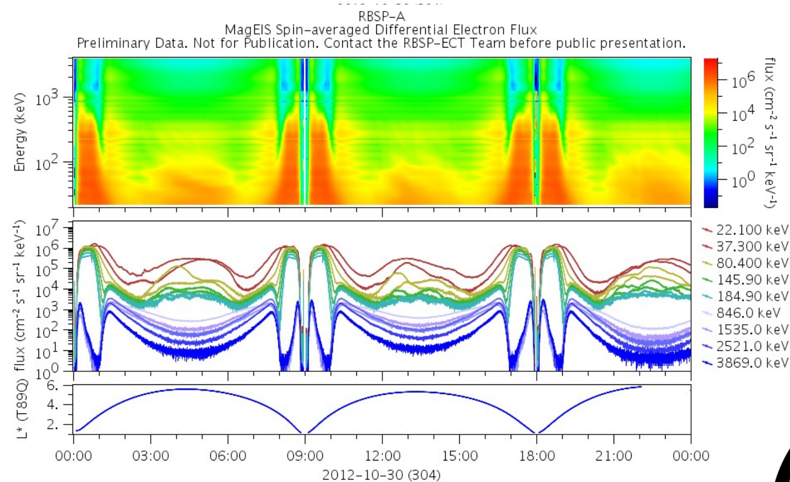
- **Products include:**
  - data products
  - summary plots
  - QA files
  - trending data

Great data; great science from RBSP-ECT

- 15+ AGU talks http://www.rbsp-ect.lanl.gov/Publications.php
- Browse the data at http://www.rbsp-ect.lanl.gov/ScienceDataL2.php







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Getting started with Python and SpacePy

- No need to throw out existing code, processes, etc.
  - Python make a great “glue” language
  - At LANL, we still use plenty of C, Fortran, IDL...
- SpacePy page: http://spacepy.lanl.gov/
- See case studies in the SpacePy documentation for extensively explained examples, cross-linked to the documentation
- Email spacepy-info@lanl.gov for general information and assistance
- This poster will be on the AGU site as an ePoster

Future directions

- Release 0.1.4 scheduled next week
  - bug fixes and little enhancements
  - PoPPy refinements
  - export from datamodel to JSON-headed ASCII
  - pybats enhancements
- Then...
  - Integration with LANLGeoMag magnetic coordinates library
    - after LANLGeoMag release
  - SeaPy enhancements
  - Official Python 3 support

References

Brambles, O. J., et al. (2010), Effects of causally driven cusp O+ outflow on the storm time magnetosphere-ionosphere system using a multifluid global simulation, *J. Geophys. Res.*, 115, A00J04, doi:10.1029/2010JA015469.

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